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MAGMATIC ORE DEPOSITS, SUDBURY, ONT.

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CONTENTS.

INTRODUCTION.

No other types of deposit have perhaps excited more scientific interest than those for which a syngenetic magmatic origin has been claimed. This is especially true for deposits of sulphides

supposed to be of magmatic origin. Geologists have had litt difficulty in accepting a magmatic origin for deposits in whic the ore minerals are also common rock-forming minerals, suc as the iron ore deposits. On the other hand, there has bee hesitancy in accepting a like origin for deposits in which the o minerals are not common accessory minerals of rocks, such sulphides. For this reason the Sudbury deposits have attracte more than usual interest,—an interest increased by the fact th these ore bodies constitute the greatest nickel deposits in t world, and because both a magmatic and hydrothermal origi have been claimed for them. Considerable controversial liter ture has appeared upon the subject, and recent contributions ind cate that the subject of origin will be reopened with renewe vigor.

For those geologists whose field experience of the Sudbur ores is limited or lacking, the more or less opposing array c published facts and conclusions offer difficulty for a clea understanding of the origin of these deposits and of magmati sulphide deposits in general. The writer finds himself in thi class of geologists, and in an attempt to clarify his mind upo the subject investigated the literature pertaining to the deposit and studied Sudbury rocks and ores by means of thin section and polished specimens. In this investigation were encountere certain conclusions supported by convincing evidence, and als opposing conclusions supported by equally convincing evidence Where the supporting evidence for both sides is strong, it i rather suggestive that a more correct conclusion would be on which includes some of the evidence presented by each side Such a conclusion has been presented by one investigator.[1]

A modification of this conclusion is presented by the writer and it is believed that it is supported by convincing evidence o both sides and meets some of the objections advanced by differen investigators.

[1] Ernest Howe, "Petrographical Notes on the Sudbury District," Econ Geol., Vol. XI., p. 503, 1914.

FIELD RELATIONS.

ROCK FORMATIONS.

Since a knowledge of the field relations of the Sudbury region is indispensable for an understanding of what is to follow, a brief summary from the writings of those who have worked most in the field is presented.[2]

The formations of the Sudbury region correspond to a great spoon with its point to the southwest. Its length is about thirty-six miles and width about fifteen miles. The center of the spoon is occupied by 9,000 feet of sandstones, shales, and conglomerates of upper Huronian age. The rim of the spoon, varying in width from one to four miles, is what Coleman has termed the "Nickel Eruptive."[3] This is an intrusive mass consisting of norite in its outer margin and grading into micropegmatite in its inner and upper margin. It is with the "nickel eruptive" that the ore bodies are more or less directly associated.

The spoon rests on a great thickness of pre-Cambrian rocks made up of a crystalline group,--largely eruptive,—of Keewatin, Grenville, and Laurentian age, and a series of sedimentary rocks chiefly quartzites, which Coleman has termed the Sudbury series.[4] Their thickness is estimated to be 30,000 feet. Included within the Sudbury series are many basic eruptives consisting of gabbro, norite, and greenstones made from basic eruptives. Coleman[5] also includes in this series acid eruptives of coarse granite-syenite and granitoid gneiss which lie directly under part of the rim of norite-micropegmatite on the south side of the spoon and form a foot wall to the norite and some of the ore bodies. The northern half of the spoon and the southeastern edge of the Lower

[2] Barlow, A. E., Geol. Surv. Can., Ann. Rep., Vol. 14, part H, 1901.

Coleman, A. P., "The Nickel Industry," Can. Dept. of Mines, Mines Branch, No. 170, 1913.

Knight, C. W., "Origin of the Sudbury Nickel Copper Deposits," *Eng. and Min. Jour.*, Vol. 101, p. 811, 1916.

See also geologic maps accompanying Coleman's report.

[3] "The Sudbury Laccolithic Sheet," *Jour. Geol.*, Vol. 15, p. 252, 1907.

[4] "The Nickel Industry," Can. Dept. of Mines, Mines Branch, No. 170, p. 6, 1913.

[5] *Op. cit.*, p. 8.

Huronian are underlain by granite gneiss and hornblende sch of Laurentian age, much older than the nickel eruptive.

STRUCTURAL RELATIONS OF ROCKS.

The sedimentary and included eruptive rocks of the Sudbu region are concluded by Barlow and Coleman to belong to t pre-Cambrian. Coleman[6] classifies the older greenstones a green schists as Keewatin; the coarse white quartzites and fi grained gray gneiss as Grenville; the Sudbury series as probal earlier than Lower Huronian; the graywacke and conglomer as Lower Middle Huronian; and the sandstones, slates, tuf and conglomerates within the spoon as Upper Huronian. T granitic rocks at the southeast edge of the Sudbury series a those surrounding the northern half of the spoon are consider by him[7] to be Laurentian and intrusive into the Sudbury but f older than the sediments and the nickel eruptive.

Included with the Laurentian granitic rocks is the granite ar in the vicinity of the Creighton mine upon which the nick eruptive is presumed to have rested. Coleman[8] considers t small area of granite between the Murray and Little Stobie mir to be later than the nickel eruptive and regards the eruptiv within the Sudbury series as being in part older and part young than the nickel eruptive.

The nickel eruptive is intrusive into all of the sedimenta rocks and is regarded by Coleman as later in age than the grani rocks which form its footwall on the northern and a part of t southern sides.

Knight[9] has more recently shown that the granite footwall the norite on the south side of the spoon is not older than t norite but is intrusive into it.

Coleman[10] believes that the nickel eruptive was intruded in t

[6] *Op. cit.*, p. 5.

[7] *Op. cit.*, p. 8.

[8] *Idem*, p. 8.

[9] "Origin of the Sudbury Nickel-copper Deposits," *Eng. and Min. Jo* Vol. 101, p. 811, 1916.

[10] *Idem*, p. 10.

form of a great sill between the ancient surface of the older rocks and the basal conglomerate of the overlying Huronian series which now occupies the center of the spoon. After the nickel eruptive reached its resting place it is proved to have undergone differentiation in situ resulting in its lower outer edge in a norite which grades insensibly into micropegmatite in its upper inner edge. Field relations show that there are roughly 3 parts acid rock to 2 parts basic rock.[11]

Later than the nickel eruptive and representing the latest phase of igneous rock processes in the region are numerous large diabase dikes which cut the norite and ore bodies[12] and are themselves cut by small granite dikes.

ORE DEPOSITS.[13]

The ore deposits at Sudbury have long been worked for their nickel and copper content. In addition platinum and small amounts of silver, gold, and palladium are won from the ores, and irridium and osmium have also been noted. The gangue is the enclosing rocks.

The Sudbury district is the source of the world's greatest nickel supply and is also an important producer of copper. The present ore reserves indicate a supply for many years to come, and development and exploratory work is continually exposing more ore bodies. Geologic conditions indicate that future work will add greatly to the present reserves so that a long life may be expected for the district.

Character of Ore Bodies.—Some of the important features in any consideration of the origin of the Sudbury ore deposits are the shapes of the ore bodies, their position with respect to the norite, the nature of the contacts between the ore and norite, and the relation of the metallic minerals to each other and to the en-

[11] Coleman, A. P., *Jour. of Geol.*, Vol. 15, p. 772, 1907.

[12] Coleman, A. P., *op. cit.*, p. 11.

[13] For the best description of the ore deposits the reader is referred to Coleman, A. P., "The Nickel Industry," Mines Branch, No. 170, 1913, from which the description of the ore bodies given here is largely drawn.

closing rock minerals. It is necessary therefore that these fea tures be reviewed.

Coleman[14] distinguishes two main varieties of ore bodie "marginal" and "offset," which he summarizes as follows:

Marginal (*a*) dipping toward the axis of the basin, ores with con paratively little rock and more than twice as much nickel as copper.

(*b*) Faulted marginal—irregular in shape and character—usuall mixed with much rock and carrying as much copper as nickel, or some times more.

Offsets: (*a*) Columnar offsets, roughly cylindrical bodies nearly ve tical and going to great depths. Ore usually rich in copper and th precious metals.

(*b*) Parallel offsets—not columnar, but sheet-like, dipping inwar toward the basic edge. Ore like that of the usual marginal deposits.

Marginal Deposits.—The marginal deposits are one of th striking features of the Sudbury district. They occur at th basic margin of the norite, so that the norite forms the hangin wall and the adjoining country rock the footwall. They all di toward the center of the basin at an average of 30°–35°. The thickness varies from a few to a hundred feet or more and the length up to 700 feet. Their depth is as yet unknown. Th Creighton ore body, which is the most important of this type c deposit, has been found to extend to a depth of at least 9c feet.[15] Coleman states[16] that the ore bodies may have a distin footwall or may penetrate it along fissures and enclose blocks c it. He considers the hanging wall to merge gradually into blending of rock and ore called pyrrhotite-norite, and then in pure norite with blebs of ore.

Howe's description of the Creighton differs from that of Col man's in that he considers the change from ore to norite to be le gradual and the

graduation to be due to a mechanical mixture of sulphides and nori in the transition zone, and not to a graduation in a mineralogical sen

[14] Coleman, A. P., Can. Dept. Mines., Mines Branch, No. 170, pp. 34 a 38, 1913.

[15] Coleman, *op. cit.*, p. 34.

[16] *Idem*, p. 34.

In all places where transition from ore to rock is supposed to exist, the norite has been extensively shattered in the neighborhood of the ore, and the sulphides appear to have penetrated the norite along the cracks and fissures so formed, while angular fragments of norite are included in the sulphides close to the rock. The veinlets of sulphides die out gradually in the norite away from the massive ore, while the rock fragments included in the sulphides become numerous and smaller in size as their distance from the hanging wall increases. There is thus a transition from ore to rock in a mechanical sense, and from a mining standpoint the expression is justifiable. Neither megascopically nor with the aid of the microscope could the writer recognize a petrographical graduation.[17]

Faulted Marginal Deposits.—Coleman[18] cites the Cream Hill and Garson mines as examples of the faulted marginal deposits. He considers these to have been formed, or begun, as the usual marginal type, "but later faults have crushed and split up the country rock and the ore wandered into the fissures between the blocks, either at the time as molten sulphides, or later through water transport." The ores are richer in copper and contain much quartz, carbonates, sphalerite, and galena "as a result of circulating waters."

Offset deposits.—The offset deposits, as defined by Coleman,[19] are dike-like masses of ore and rock that extend outward from the main norite mass into the underlying older rocks, or more or less separate bodies having no visible connection with the main norite body. The columnar offsets as at Copper Cliff and Victoria mines are pipe-like bodies, somewhat resembling the Kimberley diamond pipes, from 50 to 200 feet in diameter. In the Victoria mine have been developed to a depth of 1,400 feet. Coleman[20] states in regard to these deposits,

The contents of these pipe-like bodies differs considerably from those of marginal deposits, being more rocky, as might be expected, and containing usually more copper ore, as well as more of the precious metals, gold, silver, platinum and palladium. . . . There is usually more evidence of water action than in the marginal mines. . . .

[17] Howe, Ernest, Econ. Geol., Vol. 9, p. 514, 1914.
[18] *Op. cit.*, p. 35.
[19] *Idem*, p. 35.
[20] *Idem*, p. 37.

The parallel offset deposits are long irregular sheets of no
and ore, roughly parallel and dipping toward the main no
sheet. They are separated from the norite by other rocks
have no visible connection with it. The Frood and Stobie mi
are examples of this type.

MINERALS.

Of the minerals that compose the Sudbury ores pyrrho
chalcopyrite, and pentlandite are the most important. Of t
pyrrhotite is abundant, chalcopyrite is common, and pentlan
though scattered through all the ores, is rarely seen with the na
eye. Other minerals that occur in the district are pyrite,
casite, polydymite, willemite, niccolite, gersdorffite, magn
titaniferous magnetite, cassiterite, galena, zincblende, mol
nite, and sperrylite. In addition, the usual oxidized compo
of some of these minerals are to be found.

The pyrrhotite is widely scattered throughout the norite o
district and makes up the greater part of the ore bodies.
timately admixed with it are chalcopyrite and pentlandite.
chalcopyrite may readily be distinguished in the ore, and bu
of pentlandite may occasionally be discerned, although it is
ally revealed only by means of the microscope. All of the
minerals are more or less rare. The pyrite, galena, and
blende are usually associated with quartz and carbonat
commonly occur in veins which, according to Coleman,[21] ar
than the main ore bodies. They occur in the offset deposits
than in the marginal ore bodies.

PREVIOUS VIEWS OF THE ORIGIN OF THE SUDBURY

The scientific interest attached to the celebrated Sudbu
posits is due not only to their unique character but to the
lem of origin they present. Because of their complexity
erature concerning them is voluminous. The previous i
gators may be divided broadly into two schools; those fa
an origin by means of hydrothermal agencies, and those b

21 *Op. cit.* p. 27.

matic differentiation. Some modifications of both hypotheses have been advanced. It is intended here to mention the views pertaining to the origin of the Sudbury deposits, to outline briefly the more recent theories and then to discuss them separately.

The earlier views have been so excellently summarized by A. E. Barlow[22] that it is necessary only to refer to them without further discussion. Barlow[23] states that the first investigators, Collins, Merritt, and Bell, ascribed a hydrothermal origin to these deposits: the same origin was adopted later by Emmons, Bush, Argall, and others.

The first to advocate an igneous origin for the Sudbury deposits was Barlow, and somewhat later Vogt advanced a similar origin to explain the Norwegian deposits. Since that time Barlow's views have been advocated by Adams, Browne, Kemp, Walker, and others. In later years Coleman has carried on extensive work in the Sudbury district and is perhaps the strongest advocate of the views of Barlow. When Barlow's explanation of the origin of the Sudbury ores appeared it was widely accepted, and no dissenting opinion appeared in the literature until 1903 when C. W. Dickson[24] attacked the igneous origin. From a study chiefly by means of the microscope he concluded that the sulphides were deposited from solution. A similar study led Beck[25] to the same conclusion. Later Campbell and Knight[26] investigated the problem by a metallographic study and supported Dickson's views.

In 1911 Ernest Howe and J. D. Irving visited the Sudbury region, the former making a second trip in 1913. Some of Howe's observations, with which Irving is in agreement, were published in an article[27] in which he advocated a modified igneous origin for the Sudbury deposits. In 1916 a preliminary article appeared

22 Econ. Geol., Vol. 1, p. 454, 1906.

23 *Idem*, p. 459.

24 "The Ore Deposits of Sudbury, Ont.," *T. A. I. M. E.*, Vol. 34, pp. 1-65, 1903.

25 "Nature of Ore Deposits," p. 41, 1903.

26 "Microstructure of Nickelliferous Pyrrhotites," Econ. Geol., Vol. 2, p. 350, 1907.

27 Econ. Geol., Vol. IX., p. 503, 1914.

by C. W. Knight[28] in which, as a result of extensive field work shows that the age relations of some of the intrusive rocks different from what had hitherto been considered, and he cludes the ores are of hydrothermal origin. The latest pu cation dealing with the Sudbury deposits is that by Tolman Rogers[29] in which the ores are believed to have been for by replacement of the norite by the action of "mineralizers."

OUTLINE OF RECENT VIEWS OF ORIGIN OF SUDBURY OI

From the outline above it may be seen that the views of origin of the Sudbury ores are conflicting.

Dickson based his ideas of a hydrothermal origin chiefly the microscopic relations of the ore and rock minerals. He tained specimens from a large number of the mines, all of wh showed a brecciated character both on a large scale and mic scopic, in which the ore "prevailingly occurs as a cement brecciated rock fragments and along shear planes."[30] He fo that these included rock fragments were free from ore excep veinlets cutting across them, and in general that the sulph were most abundant where the enclosing rock was most crush Thus, his conclusion is that the shearing and brecciation t place previous to the formation of the ore bodies proper.

Microscopic work led him to conclude that the sulphi had replaced the rock minerals, particularly pyroxene and ho blende, and that in some cases, as at the Mount Nickel m pseudomorphs of sulphides after hornblende occurred. T microscope also showed that metamorphic changes and devel ment of secondary hornblende are most marked near the bodies and diminish away from them, and that the more co plete the alteration of the rock the more complete has been its placement by sulphides. He found that the sulphides tend occur in connection with the fibrous minerals, and along planes weakness. Practically all of his microscopic work sugges

[28] *Eng. and Min. Jour.*, Vol. 101, p. 811, 1916.

[29] "Magmatic Sulphide Ores," Leland Stanford University Publicati 1916.

[30] Dickson, C. W., *op. cit.*, p. 50.

that the sulphides are decidedly later than the rock minerals, but he found a very subordinate amount of pyrrhotite which he took to be an original constituent of the rock. He also concluded that the magnetite holds a different relation to the rock minerals than to the sulphides, always being in more or less rounded grains in dark rock minerals and generally primary.

Dickson points out that the chalcopyrite occurs usually in fairly pure masses and is concentrated near the outside of the ore bodies toward the footwall. This purity and concentration are considered to be due to later mineralization by chalcopyrite which entered along fractures in ore and rock. Greater copper concentration as in the Copper Cliff mine may have been due to greater fracturing and more active solutions. Dickson's description of the Creighton mine indicates a considerable amount of brecciation with numerous angular fragments of norite surrounded by ore, and notable replacement of rock by sulphides. There also, a partial replacement of an acid rock that intrudes the norite is noted.

Later Campbell and Knight supported the findings of Dickson. Their work[31] consisted of a metallographic examination of polished specimens of ores from Sudbury, Norway, and other nickelliferous-pyrrhotite localities. By this means they found that the same relations held between the minerals in all the localities studied, that magnetite was the first mineral to form, the rock silicates next, followed by pyrrhotite, pentlandite, and chalcopyrite; the rock silicates were in general fractured, the corners rounded off and the sulphides had in part replaced the slicates. They concluded that these features were the result of deposition from ore bearing solutions.

Coleman in his article[32] on the Sudbury district which appeared later strongly advocates the igneous origin of these deposits. He asserts that Dickson was unfortunate in his choice of specimens, since he selected them chiefly from offset deposits and brecciated ore bodies, and that he did not study the other phase in which

[31] "Microstructure of Nickelliferous Pyrrhotite," Econ. Geol., Vol. 2, p. 350, 1902.

[32] Rept. Bur. of Mines, Ont., Vol. 14, Part III., p. 17, 1905.

particles of ore in norite point more clearly to an igneous or
In his opinion the studies of Campbell and Knight show si
the final deposition of the minerals and affirm only that a ce
amount of fracturing of pyrrhotite allowed pentlandite and
rhotite to migrate into the fractures,[33] and he thinks[34]

that these features shown by Dickson and Campbell and Knight m
explained by a later rearrangement in which some of the minerals
dissolved and redeposited along fractures by means of circulating
tions. This rearrangement is more marked in offset deposits th
marginal ones.

Coleman's summary of the arguments in favor of an origi
the Sudbury ores by magmatic segregation are quoted.[35]

1. The ores are everywhere associated with the norite of a s
eruptive sheet. No ore occurs without norite. No long stretch o
lower edge of the norite or its dike-like offsets is entirely devoid of

2. Norite and ore are mixed in every degree from rock encl
scattered particles of ore, to pyrrhotite-norite in which ore and roc
in equal amounts, and finally to almost pure ore with a few rock-for
minerals scattered through it. This relationship is found at every
Norite spotted with ore is sometimes found in bands a long dis
from the nearest ore body and separated from the basic edge by
free from ore.

3. The adjoining rock, granite, gneiss, greenstone, or graywack
never spotted with ore, and separated bodies of ore are never enc
in it, but veinlets of ore may penetrate the country rock, and a
always blocks of it are enclosed in the ore. The shattering and cru
of the country rock took place when the nickel-eruptive forced its wa
tween the upper sediments and the lower crytalline rocks, and the he
and probably more fluid sulphides filled all the spaces thus opened.
are often clean walls of country rock against large bodies of pure

4. The freshest norite is generally close to the ore bodies and is
shotted with ore. The best preserved hypersthenes at the M
Creighton, and Gertrude mines are in sections containing sulphide
not in specimens free from sulphides at a distance from the mines.
considerable amount of re-arrangement caused by water could have
place without changing so susceptible a mineral as hypersthene
secondary minerals.

[33] Can. Dept. of Mines, Mines Branch, No. 170, p. 30, 1913.
[34] Rept. Bur. of Mines, Ont., Vol. 14, Part III., p. 10, 1905.
[35] *Op. cit.*, p. 18.

5. The marginal ore bodies show hardly a trace of hydrothermal or pneumatolytic action. There are seldom any of the minerals usual in deposits formed by water except very small quantities of quartz and calcite, and these are often in seams cutting the ore and evidently of later formation. There is no banding such as one finds where cavities are filled with minerals deposited from solution; nor are there concentric structures about the rock fragments enclosed in the ore.

6. The deposits are extremely uniform as shown by Dr. Barlow, a fact hard to account for in mines scattered along a length of 35 miles with entirely different country rocks on one side unless they have had a single source, the norite, which is as monotonous as the ores themselves.

7. The largest ore bodies are where bays of the norite project into the country rock or on offsets from such funnel-like bays; there is seldom a deposit of importance along a straight margin; and no ores are found on parts of the margin which project inwards instead of outwards. This is intelligible if the ore settles into the hollows under the molten sheet, but quite unaccountable if it was brought in solution from elsewhere along the channels furnished by the contact.

From field and microscopic evidence Howe[36] found nothing to suggest that the ore bodies had been formed by replacement of the norite, nor did microscopic evidence indicate a gradation from norite to massive sulphide in a petrographic sense. He also notes the brecciated character of the Creighton ore body and states that veinlets of sulphides penetrate the norite hanging wall and norite fragments included in the ore.

As a result of these investigations Howe[37] proposes a modification of the magmatic theory. He suggests

that the molten sulphides were originally introduced into their present position in a molten condition. The brecciated character of the contacts between ore and country rock, as well as the fineness of the grain of the norite close to the contact would seem to indicate that the sulphides were intruded after the norite had cooled and that they represent, perhaps, an end product in the differentiation of the magma from which the norite was derived. In other words, the differentiation, of sulphides and silicates at least, was affected in the magmatic reservoir and not in the laccolithic chamber. This modified hypothesis in Howe's opinion would relieve the theory of magmatic origin of the burden of many troublesome problems in physics and chemistry.

[36] Econ. Geol., Vol. 9, p. 503, 1914.

[37] *Idem* p. 521.

Again in Knight's[38] latest contribution to the subject we f
a further advocating of the hydrothermal origin of the depos
As a result of recent field work he has found that the gran
footwall of the Creighton ore body upon which, according to
magmatic theory, the molten sulphides are supposed to h
settled out of the magma, is not older than the norite as has b
assumed, but is younger. He says:[39]

> Clearly then, since the granite is younger than the norite, the mo
> sulphides could not have settled to the bottom of the norite magma
> rested on the granite footwall, for the very good reason that the gra
> was not there when the norite was erupted.

He also states at the Frood or No. 3 mine the ore is not wh
in norite, as has been supposed, but occupies a crushed zone
schistose beds of graywacke and to be a less extent in nor
Some of the sulphides also impregnate the basic intrusives.
brecciated character of the Worthington mine is pointed out,
it is emphasized that sulphides are spotted in granite, greenst
and graywacke in a similar manner to the spotting of norite
much emphasized by Coleman as an indication of magm
origin. From these and other data to be dealt with in a for
coming paper, Knight concludes the deposits to be of hyd
thermal origin.

The latest publication dealing with the Sudbury ores is that
Tolman and Rogers.[40] From microscopic work with thin s
tions and polished specimens they conclude that the sulphi
are all later than the rock minerals and that they have b
formed by a replacement of the silicates, and that in general
later formed ore minerals replace the earlier ore minerals.
addition to replacement in all degrees of completeness they
cord veinlets of sulphide cutting across the rock silicates. T
also find that the order of formation of the minerals is silica
magnetite and ilmenite, pyrrhotite, pentlandite, chalcopyr
An absence of hydrothermal and pneumatolytic alteration of

[38] *Eng. and Min. Jour.*, Vol. 101, p. 811, 1916.

[39] *Idem*, p. 812.

[40] "Magmatic Sulphide Ores," Tolman, C. F., Jr., and Rogers, A.
Leland Stanford Jr. Univ. Publications, 1916.

rocks accompanying the metallization is noted but such alteration has occurred to a limited extent after the formation of the sulphides.

Tolman and Rogers disagree with Dickson "as to the hydrothermal 'secondary aequous' origin of the ores" but agree "with the supporters of the magmatic hypothesis that the ores were formed within the magmatic period. They were, however, not formed at an early stage and not by the sinking of the sulphide constituents."

Their conception is that the ores were formed at a late magmatic stage by the action of "mineralizers," and that the sulphides replace the silicates. While they apply the term "magmatic" to these deposits, they do not imply the usual significance of the term, and while they consider them to have been formed by replacement as a result of "mineralizers" or "mineralizing solutions," they differentiate from the usual replacement in that no hydrothermal alteration took place at the time the ores were deposited.

DISCUSSION OF RECENT VIEWS.

From the above summary of some ot the recent views regarding the origin of the Sudbury ores, it will be seen that they are conflicting and there is much that is plausible and convincing on each side, while no one theory adequately explains all of the evidence that has been produced. It would appear also that no one view can be completely discarded. Some of the points for and against each hypothesis will therefore be discussed.

MAGMATIC SEGREGATION.

The hypothesis of magmatic segregation has in its favor the close association between ore and norite. As pointed out by Coleman practically all of the ore bodies are in or immediately adjacent to norite, and no part of the main norite mass or its dike-like offsets is entirely devoid of ore. While this same association is true to some extent of deposits clearly not of magmatic origin, as the disseminated copper ores in porphyry intrusions such as

at Bingham, Utah, where some sulphides are scattered throu
practically all of the monzonite porphyry, it is nevertheless
strongly suggestive argument. Another suggestive argument
favor of magmatic segregation is the more or less world w
association of norite and nickeliferous pyrrhotite, in which t
sulphides are invariably at or near the border of the norite
far as is known there is no conclusive evidence against sulphid
such as occur at Sudbury, forming a part of an igneous rock a
occurring in a molten condition. On the contrary many inves
gators have produced evidence from widely scattered localit
showing that sulphides do occur originally in igneous rocks. A
David Browne has shown that in a pot of matte the nickel ten
to concentrate toward the center and the copper toward the m
gins, simulating the conditions of occurrence of the Sudbu
ores.[41]

That the nickel eruptive itself has undergone a differentiati
from norite to micropegmatite is disputed by none. The arg
ment of further differentiation of sulphides from norite is the
fore reasonable and suggestive though by no means conclusi

One of the most noticeable features in connection with all o
bodies formed by hydrothermal processes is the pronounc
alteration which the containing rock has undergone. This
especially true of deposits where the sulphides are more or l
scattered through the rock as is the case in the Sudbury depos
As Coleman points out "no considerable amount of rearran
ment caused by water could have taken place without chang
so susceptible a mineral as hypersthene into secondary m
erals."[42] Therefore the paucity of a pronounced and inter
alteration of all the norite surrounding the ore at Sudbury is
argument against the hydrothermal origin of those ores and m
be construed as an argument in favor of magmatic segregati
though it cannot be used exclusively in favor of such an orig

The scarcity of such ore minerals in most of the Sudbury mi
as are commonly indicative of deposits of hydrothermal ori
is a further indication that these deposits are not to be classed

[41] *Columbia Univ. School of Mines Quarterly*, p. 270, 18[illegible]5.

[42] Coleman, A. P., Rept. Bur. Mines, Ont., Vol. 14, p. 18, 1905.

entirely of hydrothermal origin. This argument in conjunction with other criteria might be suggestive for a magmatic segregation origin, though again it cannot be considered as a conclusive proof in favor of it.

The lack of banding and concentric and preserved structures, such as characterize ores deposited in open cavities or by replacement, and the lack of drusy filled cavities, is suggestive of an origin other than hydrothermal, but cannot necessarily be used as a proof of magmatic segregation, as has been done by Coleman and others, any more than it could be used as a proof of contact metamorphic deposits.

One of the strongest arguments advanced by the advocates of magmatic origin is that there is in most cases a transitional phase of pyrrhotite-norite between the norite proper and the ore, and that this merges gradually into pure norite on the one side and into ore on the other. The fact that the ore bodies terminate fairly abruptly against the footwall rocks and fade out into the hanging wall norite is an argument against a hydrothermal origin and in favor of magmatic segregation. Howe has shown that in the Creighton mine this is a mechanical fading out and not a petrographic one as contended by Coleman. Specimens examined by the writer support a part of Coleman's contentions and indicate that while the main ore bodies fade out mechanically beyond them there is pyrrhotite-norite in which the pyrrhotite gives every appearence of being an original constituent of the rock. Knight, on the other hand, states that the granite, greenstone, and graywacke of the footwall are also spotted with sulphides in a manner similar to the pyrrhotite norite. It is clear, however, that the larger part of the ore bodies are in the norite and that there is a greater proportion of fading out into norite, whether mechanical or petrographical, than into the footwall rocks. The statements of Howe and Knight just quoted, invalidate to considerable extent the strength of the argument of fading out as a proof of magmatic segregation.

The uniformity and monotony of the ores and minerals over such a wide area in Sudbury is suggestive of an igneous origin. It is difficult to understand how ores deposited from solutions

which must necessarily be subject to fluctuating condition
composition, concentration, temperature, and pressure coul
so uniform all around the norite intrusive.

The indisputable evidences of water action as shown in n
of the deposits is explained by the advocates of magmatic se
gation by a later rearrangement by hydrothermal waters rele
from the magma during its solidification. By these solutions
valuable minerals are assumed to have been dissolved, tr
ported, and redeposited in other places along with typical hy
thermal minerals, thereby bringing about a concentration of
ores, but by no means accounting entirely for the origin
position of the present ore bodies.

In all of his writings Coleman has emphasized the marg
position of the ore bodies with respect to the intrusives, and
pointed out that the largest ore bodies are where bays of n
project into the country rock or on offsets from such funnel
bays. These points are used as one of the arguments for m
matic segregation. This marginal distribution is difficult
satisfactory explanation by any other than the magmatic th
and is one of the strongest points in its favor. It may be poi
out, however, that a more or less marginal occurrence of hy
thermal pneumatolytic ore bodies around intrusives is not
usual, for example, most tin deposits have a marginal pos
with respect to the intrusive.

The offset deposits extending outward from the funnel
bays in the bottom of the norite are also used by the advoc
of the igneous origin as suggesting magmatic segregation. C
man[43] considers them to have been formed by a shattering of
underlying rock produced by its "collapse during the remova
the molten rock from beneath and also by the mechanical ac
of the laccolithic sheet spreading out above." These fract
are believed to have "drained" off the molten sulphides
norite, thereby giving rise to dike-like forms of norite and
constituting the offsets. He states:

> The fissures and devious channels between the blocks woul
> flooded by the highly fluid norite and ore acting under the pressu

[43] Can. Dept. of Mines, Mines Branch, No. 170, p. 36, 1916.

three miles of overlying magma and solid rock. The bottom norite highly charged with sulphides entered and filled every existing channel and forced its way in places through belts of shattered and weakened rocks enclosing many fragments torn off on the way.

Examination of this explanation discloses a weakness in its advocacy for magmatic segregation.

If the fracturing took place due to the removal of the magma beneath, or by the mechanical action of the overlying sheet, it must have taken place shortly after the intrusion of the nickel eruptive. Such fractures then would be expected to be filled first by the original undifferentiated magma, since differentiation in situ such as occurred in the nickel eruptive could not have taken place immediately, and considerable time must have elapsed before the norite and sulphides were segregated at the bottom in a position to enter the underlying fractures. Thus one must conclude that the fractures must either have first been filled by such a magma and later displaced by the basic phase, or, that the fractures were delayed in their formation until just the proper moment when the differentiation has proceeded sufficiently that the norite and sulphides were segregated at the bottom, or, that offsets cannot properly be accounted for by the explanation given.

The first two possibilities do not seem probable. If the fracturing be presumed to have resulted from the intrusion and the undifferentiated magma once entered these long narrow dike-like openings, where cooling would take place rapidly, it seems improbable that it could later be displaced entirely by a differentiated product of norite and ore without some evidence of the undifferentiated magma being left behind for it is clear that, due to the rapid cooling or freezing of magma on its walls, the outermost portion represents the undifferentiated magma. There is evidence in the fine-grained character of the norite near its margins the rapid cooling has taken place. Yet as far as can be learned there is no evidence of any undifferentiated magma or any indication that the fractures were first filled by such an undifferentiated magma. The very fact that the norite and ore have markedly fine-grained marginal phases indicates their contact with relatively cold rocks, and this would not be expected had differen-

tiation taken place in situ where the walls would become high
heated long before differentiation had proceeded sufficiently f
to bring the differentiated norite and ore to the outside. Co
man[44] uses this chilled edge of ore and norite as a proof of ma
matic segregation. While it certainly indicates, or at lea
strongly suggests, that the ore was in a molten condition, it d
not favor the theory of magamtic segregation as much as
favors the modified theory of magmatic differentiation advanc
by Howe.[45]

Its fallacy as an argument for segregation is further shown
Knight's findings that the granite footwall against which the
in the Creighton is presumed to have been cooled is later in a
than the norite. It is therefore proof that the ore must be lat
in age than the norite. The other possibility, mentioned abo
seems too delicate an adjustment to be probable that the fractur
should just open up at the particular phase of the completion
differentiation ready to receive the lower basic differentiate
norite and sulphides. Thus it would appear that the offset
posits cannot be assumed to have been formed as explained
Coleman and therefore are no argument in favor of magma
segregation.

Another argument advanced by Coleman and others in fav
of magmatic segregation is the ore breccia, so much described
all who have written on Sudbury, in which fragments of oth
rocks are enclosed by ore and norite. This is considered by Co
man[46] as "due to the faulting and smashing of the underlyi
rock owing to the motions of the nickel bearing magma in reac
ing the present position," and by "the bottom norite high
charged with sulphides . . . enclosing many fragments torn off
the way. Doubtless there was much grinding of one surfa
upon another in the process, accounting for the many round
boulder-like fragments enclosed in the ore."

If the ore be assumed to have been formed by magmatic segr
gation then a considerable time must have elapsed between t

[44] Op. cit., pp. 33 and 37.
[45] Op. cit.
[46] Op. cit. pp. 34 and 36.

segregation and the first intrusion of the magma. For a marginal segregation of ore to have taken place either by gravity, convection, sinking crystals, or any other method, the magma of sulphides must have been in a relatively quiet of passive state and incapable of vigorously tearing off great quantities of fragments from the walls. Differentiation postulates a quiescent rather that vigorously moving magma. Also the fragments of rock in ore cannot readily be explained according to Coleman's idea for the reason that although the motions of the nickel-bearing magma, in reaching its present position, would probably enclose fragments torn off on the way, These fragments would be contained in the undifferentiated magma and not in that portion (the ore) which could not at this stage have been differentiated. Therefore the breccia in the view of the writer is opposed to magmatic segregation of ore in situ.

HYDROTHERMAL ORIGIN.

Dickson, as the first strong advocate of the hydrothermal origin based on microscopic work, finds several features irreconcilable with a magmatic origin, which in his opinion indicate the deposits were formed by hydrothermal agencies.

The microscopic evidence which he finds of replacement of the rock forming minerals by sulphides after hornblende and as a network of veinlets, strongly suggests that they were carried in solutions.

The development of secondary hornblende in the vicinity of the ore and the more complete alteration of the rock where replacement by sulphides has been more complete is another argument strongly favoring hydrothermal origin.

The presence of secondary quartz and calcite in the ore, but scarcer at a little distance from it, further suggests some relation between the ores and hydrothermal solutions. The amounts of these minerals are very subordinate to the sulphides of the camp as a whole, but in the one or two mines play a prominent part.

The widespread brecciation and shearing in which ore cements rock fragments and occurs along shear planes is certainly a strong

argument against magmatic segregation, but on that accou
not necessarily an argument in favor of hydrothermal origi
applied by Dickson, for it may apply equally well to the mod
magmatic hypothesis proposed by Howe. The angular shap
the included rock fragments is considered by Dickson to be
cult to imagine on the basis of magmatic segregation. It w
be equally difficult to imagine them having an angular for
they are residuals of a rock that had been replaced by ore
means of solutions. Replacement nuclei are usually smoo
and rounded by the replacing solutions.[47]

Again, Dickson uses as arguments in favor of hydrother
origin the abrupt change so often noticed from massive sulph
to barren rock; that sulphides are practically lacking in the
a short distance away from the ore, and that included rock f
ents are comparatively free from ore, except in veinlets. T
points are certainly opposed to a magmatic segregation, but
not necessarily indicate hydrothermal origin. The concentra
of copper however in the form of veinlets traversing norite
pyrrhotite suggests solutions.

Thus Dickson's paper on the whole produces many argum
which oppose magmatic segregation, but do not necessarily
hold the hydrothermal origin. It also gives many argum
which indicate that hydrothermal solutions have been a facto
the formation of the Sudbury ores.

The work of Campbell and Knight[48] also suggests the hy
thermal origin in showing that the sulphides occur later than
rock silicates and in the definite order of pyrrhotite, pentlan
and chalcopyrite. Further, the replacement of one sulphide
later sulphides and the replacement, rounding off, and filling
fractures of rock silicates by sulphides, suggest hydrother
solutions.

A further appeal for a hydrothermal origin is to be foun
Knight's latest contribution,[49] where the chief argument is

[47] Irving, J. D., Econ. Geol., Vol. 6, p. 527, 1911.

[48] "Microstructure of Nickelliferous Pyrrhotites," Econ. Geol., Vo
p. 350, 1907.

[49] "Origin of the Sudbury Nickel-copper Deposits," *Eng. and Min. J.*
Vol. 101, p. 811, 1916.

the magmatic segregation theory "is untenable owing to the structural and age relationship of the rock." It is shown, for the Creighton mine, that the "molten sulphides could not have settled to the bottom of the norite magma and rested on the granite footwall, for the very good reason that the granite was not there when the norite was erupted." Since ore penetrates the granite, and Knight shows the granite intrudes the norite, it is clear that the ore must be later than both norite and granite, and cannot therefore be a segregation from the norite. Knight's work demonstrates this point very clearly. These structural relations of the granite and norite have led Knight to conclude that not only is the magmatic segregation theory untenable, but the ores were formed in "a period of ore formation, during which solutions circulated along and near the contact of the granite and norite and deposited the nickel and copper sulphides which form the ore body."

While the structural relation of the granite and norite, brought out in this theory, deals a fatal blow to the magmatic segregation hypothesis, it does not necessarily follow that because a rival view is vanquished, the conclusion of a hydrothermal origin is the only alternative, for it supports Howe's modified magmatic theory just as much as the hydrothermal.

Knight also emphasizes the occurrence of ore in the Worthington mine which by its structure and mineral composition indicates hydrothermal action. All writers agree that the Worthington ores have been affected, if not largely formed, by solutions.

Knight's evidence that the sulphides mix with older greenstone and graywacke and younger granite in the same manner in which they mix with the norite certainly argues against a magmatic segregation, but again an argument against one theory does not support an opposing theory, unless there be positive evidence in its favor as well.

The writer agrees with Knight in so far as he shows the magmatic segregation hypothesis to be untenable, but fails to find in his arguments positive evidence actually supporting a hydrothermal origin for all of the deposits. Until such is forthcoming

the writer concludes that Knight's evidence supports How modified magmatic hypothesis as much as the hydrothermal.

MODIFIED MAGMATIC ORIGIN.

Howe's interpretation[50] of the occurrence of the Sudbury o differs somewhat from that of other observers. He found th in the Creighton mine there is no gradation from ore to nor in the petrographic sense, but there is a gradation due to a mec anical mixture of ore and rock. He considers that the intim mixture of fragments of granite, greenstone, and norite in the o precludes a metasomatic origin and that the microscopic wo strongly suggests the sulphides were originally introduced in molten state. To explain all these conditions he propsed interesting modification of the magmatic hypothesis whi accounts for the ore as having been introduced in a molten co dition through a differentiation in the magmatic reservoir, af the norite had cooled. Thus the ore would be considered a magmatic differentiation product though not a magmatic seg gation in situ.

This igneous theory certainly accounts for the ore breccia, which fragments of rock are cemented by ore, and explains numerous veinlets of ore which cut across rock fragments a penetrate the footwall rocks. The offset deposits may also readily explained by this theory. It accounts for those ma troublesome arguments already considered which the advoca of the hydrothermal theory have brought against the magma segregation hypothesis and applied as points in favor of alternative hydrothermal theory. As pointed out previously argument against the magmatic segregation theory does necessarily imply that it favors the hydrothermal theory. T modified theory of Howe's explains many such points that equally incompatible with the hydrothermal hypothesis.

The evidence produced later by Knight[51] that the footv granite at the Creighton mine intrudes the norite does not

[50] "Petrographical Notes on the Sudbury Nickel Deposit," Econ. G Vol. 9, p. 503, 1914.

[51] *Op. cit.*

validate Howe's hypothesis. On the contrary such evidence is directly in keeping with it if the ore be regarded as having been intruded after the granite, thus placing it in the same age relation to the norite and granite as does Knight in his hydrothermal theory.

While Howe's hypothesis relieves both the magmatic and hydrothermal theories of many objectionable features, it does not account for the marginal position of the ore bodies with respect to the norite. One would expect if the sulphides were intruded in a molten condition later than the norite that they would not necessarily have any relation whatever to the margins of the norite, while the magmatic segregation postulates such a marginal position.

Inasmuch as Howe's paper deals chiefly with petrographical notes of the Sudbury region he does not sum up or discuss evidence in favor of or against his suggestive hypothesis; consequently he offers no explanation as to how his hypothesis would reconcile the marginal position of the ore bodies.

The structural relations at the Creighton mine, which Howe advances his modified magmatic hypothesis to explain, might also be accounted for by the magmatic segregation theory if in that process the segregated sulphides be presumed on account of their lower fusion points to have remained molten longer than the hanging wall norite. They might then intrude and enclose fragments of already solidified norite.

MODIFIED HYDROTHERMAL ORIGIN.

Tolman and Rogers[52] believe they reconcile the almost diametrically opposite views of the supporters of the hydrothermal and magmatic segregation theories. They believe that the ores are magmatic, yet formed by means of "mineralizing solutions" or mineralizers. They state that the sulphides surround, cut across, and replace the rock silicates and are therefore later than them, and they present microscopic evidence which they interpret to indicate that the sulphides were formed before the hydrothermal

[52] *Op. cit.*, p. 15.

alteration of the rock silicates. This is based on their obse
tion that pseudomorphs of tremolite and possibly talc
formed as a hydrothermal alteration product after hyperstl
and that chalcopyrite, which cuts across the pseudomorphs i
form of veinlets, has not wandered into the cracks of the tr
lite, and is therefore earlier than the alteration. They w
thus place the period of mineralization after the consolidati
the norite, and before the hydrothermal solutions, which
anated as an after effect of the intrusion. They consider
the ores are not magmatic in the usual sense, because they
later than and replace the rock silicates. They believe that
were deposited by "mineralizing solutions" because of
regular order in which the sulphides are deposited one afte
other, and the fact that one replaces the other.[53] They d
consider them to be ordinary hydrothermal deposits becaus
formation of the sulphides is thought to precede the hydrothe
alteration of the rock silicates. They also think the sulp
could not have been intruded in a molten state as suggest
Howe, because there is no evidence of the metallic silicates
reaction rims which they believe should result by contact o
molten sulphides with the rock silicates and earlier sulphides

In retaining the term "magmatic" to fit in with their
ception of the Sudbury deposits, they deprive it of its custo
usage. Accepting for the moment the interpretation of the
given by Tolman and Rogers, there is more justification in
ing them hydrothermal rather than magmatic, inasmuch as
are considered to have been transported and deposited by mi
izing solutions in the same manner that any hydrothermal
its have been formed. They separate this type from the h
thermal hypothesis advocated by others, because they find
of alteration of rock silicates accompanying the deposition
ores. While this is clearly a distinction in the effects of h
thermal mineralization, it does not appear to the writer to j
a different type of process, for the customary usage of h
thermal processes does not imply rock alteration as an ess
part of the process.

[53] *Idem*, p. 15

The writer is thus unable to see in what way the arguments of Tolman and Rogers establish any but a hydrothermal origin for the Sudbury ores, and it is not clear to him how their hypothesis reconciles "the almost diametrically opposite views" of the magmatic segregation and hydrothermal processes.

Their hypothesis certainly does not account for the marginal position of the ore bodies with respect to the intrusive nor does it give any explanation for the connection between ores of this type and the norite gabbro magmas. Tolman and Rogers lay particular emphasis on the replacement of the rock silicates by the sulphides while Barlow, Dickson, Coleman, and others in their microscopic descriptions consider that the sulphides are original constituents in the rocks and have not formed by replacement. Howe's careful microscopic work[54] revealed only one certain instance of replacement of rock silicates by sulphides. An examination by the writer of several thin sections and polished specimens revealed only two instances in which replacement seemed certain to have taken place. It must be concluded then that the abundant evidence of replacement noted by Tolman and Rogers cannot be typical of all the Sudbury ores. In view of the evidence shown by others it is incorrect to apply broadly the theory of replacement to explain all of the Sudbury ores.

SUGGESTED MODIFIED HYPOTHESIS FOR ORIGIN OF SUDBURY ORES.

From the above discussion of the different views advocated for the origin of the Sudbury ores it may be seen that their genesis is complex and that there is much conflict of opinion regarding them, both as to interpretation of data and observations. The opposing hypotheses set forth an array of arguments and facts that is persuasive when one hypothesis alone is considered. All of them present plausible and convincing points which are not explained or set aside by the opposing arguments and are worthy to stand in any consideration of origin of the Sudbury deposits. It thus appears to the writer that an hypothesis that would embrace the convincing arguments of the opposing views, if in

[54] Econ. Geol., Vol. 9, p. 511, 1914.

agreement with other observations, would be a correct one. Accordingly he presents a modified hypothesis, which foll Howe's and embraces and combines some of the features of others:

A magmatic reservoir may be presumed to have underlain Sudbury region and to have contained a magma of proix intermediate composition. Differentiation of this magma in reservoir took place, but before it was completed a portion o was extruded to form the "nickel eruptive." The extru portion then continued to differentiate in its upper chamber gave rise to the differentiated intrusive as described by Barl Coleman and others with micropegmatite grading downward i norite. The sulphides, chiefly pyrrhotite, contained in this mag became segregated at the lower portion of the norite, ther accounting for the pyrrhotite norite and perhaps a minor par the ore bodies. In the meantime differentiation proceeded the remainder of the magma in the reservoir below, and magma may be considered to have divided itself into an acid basic portion, much as did the portion previously extruded.

A further extrusion then took place, and the acid portion injected between the already solidified norite and the greensto a probable line of weakness. Upon consolidation it gave ris the later granite described by Knight. Following this, the pr ess as conceived by Howe may be considered to have ta place, and a further expulsion of the basic portion from the re voir occurred. This consisted of a magma overloaded with phides which, by consolidation, formed the greater part of ore bodies. The peculiar pegmatitic inclusions described Howe may represent some of the rock matter that was extru with the sulphides. Still later expulsions would give rise to dikes which cut the ores and previously intruded rocks

Where igneous intrusion and differentiation has taken pl a usual after effect representing the final extracts is hydrother solutions. The solutions from the Sudbury magma reserv similar to those which have formed most ore deposits, would c tain some metallic minerals, and their circulation along the l of previous intrusions might superimpose on the previo

[illegible] deposits those hydrothermal effects described by Dickson, Knight, Tolman and Rogers, and others

This modified hypothesis would thus explain the ores by magmatic segregation, magmatic differentiation in the magma reservoir, and hydrothermal action, but the greater part of the ore bodies would be accounted for by Howe's hypothesis of differentiation in the reservoir and intrusion as a sulphide magma. The sequence of igneous events might be diagrammatically expressed as follows:

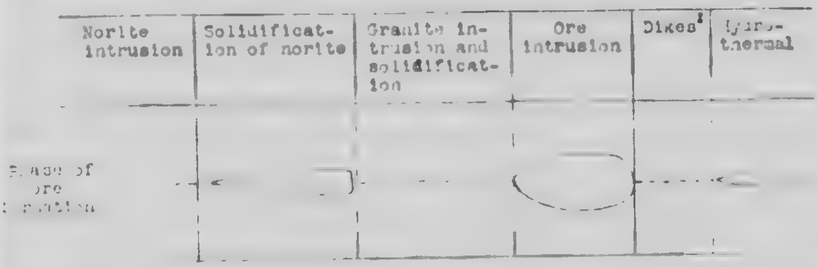

FIG. 16. The dikes which cut the ore are placed in this table previous to the hydrothermal solutions which brought in those typical hydrothermal minerals, but in the absence of definite statements concerning these relations, this position may be incorrect and they may have been intruded during or after the period of hydrothermal mineralization.

In the hypothesis proposed above there remains the difficulty of accounting for the marginal position of the ore body. This position may have been brought about by the intrusion of the molten sulphides with some rock matter, along the zones of easiest access. The contact between the norite and adjacent rocks would probably be places of weakness favorable for such intrusion. This contact may have been rendered especially weak by fracturing brought about by the collapse of the floor or by the withdrawal and settling down into its conduit of the magma after its intrusion, thus causing a slumping of the intruded mass and its overlying sediments, giving it its spoon-like form. Such slumping would cause a rupturing along the margin of the intrusive and give rise to zones of weakness where later intrusives, such as an intrusion of molten sulphide with some rock matter,

could take place. Thus the earlier sulphide intrusions woul
in part, be superimposed upon the earlier sulphide segregatio

DISCUSSION OF PROPOSED HYPOTHESIS AND RELATION
TO OTHER HYPOTHESES

The proposed hypothesis would account for the pyrrhoti
norite described by Barlow, Coleman, and others and for the s
phide particles so widely distributed along the margin of t
norite by the first phase of mineralization or the magmatic seg
gation which took place in the nickel eruptive after its extrusi
The main marginal ore bodies such as the Creighton and the
set bodies would be accounted for chiefly by the second phase
mineralization or Howe's suggestion of the intrusion of sulphi
combined with some rock matter. Thus the objection raised
Coleman.[55] that Howe's hypothesis does not explain the pyrr
tite norite, is met by the first phase of mineralization, while
second phase as shown by Howe would account for the breccia
character of the ore bodies in which fragments of rock are s
rounded and penetrated by the sulphides.

This brecciated character alone would not be sufficient supp
for Howe's theory. As previously mentioned such a struct
could well be formed according to the segregation hypothesis
the sulphides, on account of their lower fusion point, remai
fluid longer than the norite and penetrated the consolidated no
thus including and surrounding particles of it. However, s
Knight shows the granite to be later than the norite and the o
later than the granite, then the ore is obviously later than
main norite intrusion and therefore could not be explaine
segregation, but under these circumstances is readily expla
by Howe's hypothesis.

As previously pointed out by the writer on page 408 the
that the narrow dike-like openings are filled by sulphides an
by the original undifferentiated intrusive is an objection t
magmatic segregation but is readily explained by Howe's pa
the hypothesis. Also the inclusions of rock in ore as pointe
on page ~~22~~ 4 would be expected in undifferentiated magma

[55] Econ. Geol., Vol. 10, p. 390, 1915.

n the differentiated sulphides, according to the segregation thesis. They would however, be expected to occur in the hide in the same way that fragments of invaded rock are con- d in any intrusive under the sulphide intrusion hypothesis. act the matrix of ore enclosing fragments of rock, pictured by man on Plate XVIII. of his article,[56] would appear to be a intrusion breccia if it were not stated that the matrix is pyr- tite. Also Howe[57] points out that it is difficult to understand the fine-grained border texture of the norite could develop der the segregation hypothesis, but such is readily understood nsidering the sulphides to have been intruded between the usly formed chilled edge of the norite and the underlying ks.

The puzzling siliceous inclusions in the sulphides described by Howe[58] and discussed by Coleman[59] and Tolman and Rogers[60] considered by Howe to be inclusions of footwall granite, and Coleman and Tolman and Rogers to be differentiates of the . Taken into consideration with the hypothesis outlined they might also be explained in harmony with both Howe Coleman as the consolidation of some of the rock magma accompanied the intrusion of molten sulphides. Such a magma would undoubtedly contain characteristics of the granite footwall earlier differentiated from it below, and of the norite still earlier differentiated from it in the magmatic reservoir. In the same way may be explained the constant inclusion in the pyrrhotite of small amounts of rock silicates such as pyroxene and plagioclase mentioned by Coleman.[61]

The offset deposits can be readily explained by Howe's part f the hypothesis, but as pointed out on page 409 are difficult of explanation by the segregation theory. As Howe points out[62]

"The Nickel Industry," Can. Mines Branch, No. 170, p. 49, 1914.

Op. cit., p. 515.

Idem, p. 518.

Econ. Geol., Vol. 10, p. 390, 1915.

Op. cit., p. 26.

Can. Dept. of Mines, Mines Branch, No. 170, p. 30, 1913.

Econ. Geol., Vol. 9, p. 522, 1914.

"intrusion by sulphides is essentially the explanation giv
Coleman to account for certain of the offset deposits."

The observations of Dickson's[63] that the sulphides are
developed where crushing is most pronounced and that or
vailingly occurs as a cement for rock fragments and along
planes, support Howe's part of the hypothesis and are n
plained by the segregation theory. While Dickson presents
arguments in support of the hydrothermal theory, the a
character of the included fragments suggests inclusions
intrusion rather than nuclei of unreplaced rock. The abu
evidence, presented by Dickson and others, of veinlets of sul
seaming included fragments of rocks and penetrating m
cleavages would be expected from sulphide intrusion as w
from hydrothermal action so that the proposed hypothesi
bines those features advocated for the hydrothermal orig
antagonistic to the segregation theory.

The remarkable freshness of the norite surrounding the
noted by Barlow, Walker, Coleman, Howe, Tolman and R
and others.[64] This feature may be readily understood if
be considered as an intrusion but is not readily explained
the ores were formed by means of hydrothermal agencies.
Coleman points out, the susceptible hypersthene would
succumb to alteration. While in many places hydrot
alteration of the norite is almost entirely absent, some effe
is shown by the alteration of the pyroxenes in most parts
district, particularly in the offset deposits. As compa
the universally widespread rock alteration accompanyi
deposits of unquestionable hydrothermal origin, howev
paucity of such alteration in the Sudbury deposits render
ficult to accept a hydrothermal origin to account for all
ores.

Also Howe[65] and Tolman and Rogers[66] show that the
thermal alteration is later than the formation of the sulp

[63] T. A. I. M. E., Vol. 34, p. 50, 1903.
[64] Op. cit.
[65] Op. cit., p. 513.
[66] Op. cit., p. 35.

...l another point that suggests an igneous origin for most of ...es in preference to a hydrothermal one is the absence of the ...ue minerals that usually accompany hydrothermal ores. ... an igneous origin the only gangue to be expected would be ...k accompanying the sulphide magma such as is found in ...res.

...he replacement of rock silicates by sulphides is strongly ...ed by Dickson, Tolman and Rogers, and Campbell and Knight ...r of hydrothermal agencies. On the other hand, Howe, ...s, Walker, and Coleman find little evidence of replace... The writer's examination by means of thin section and ...ed specimens indicated a very minor amount of replace... There thus appears to be some ore that is not a result of ...acement and other ore that has replaced the rock silicates. The ...ter observed under the microscope two instances in which rock ...tes were embayed by sulphides similar to the embayment ...ommonly observed in quartz phenocrysts in a granite por... Whether this embayment is due to resorption or replace... is difficult to determine, but whatever the process in detail ... certain the embayment or resorption of quartz phenocrysts is ...agmatic phenomenon and not a replacement brought about by ... circulating solutions. It may be that much of that which ...alled replacement of the norite by sulphides has been brought ...out by a similar process and need not be attributed to hydro...ermal solutions. It is conceivable that the sulphide magma ...th its small amount of rock magma could corrode or replace ...he rock silicates giving rise to much the same effect produced by hydrothermal solutions. It is well known that in smelter practice molten matte, mostly sulphides, readily corrodes siliceous and basic linings of converters. Tolman and Rogers[67] lightly ...smiss corrosion as a possibility because they consider it "should produce metallic silicates by reaction" and "no such metal-bearing slag is found, and the agency that brought in the sulphides removed the dissolved silicates, all of which indicates active mineralizers." It seems more probable if a metal-bearing slag had

67 "A Study of Magmatic Sulphide Ores," Pub. Stanford Univ., p. 15, 1916.

formed that it would have been carried along and removed heavily charged sulphide magma. It is suggested that th ence or absence of such a slag would depend entirely up condition of the magma, and if the conditions were in suc cate adjustment that the magma were just about to s when the slag was formed, a reaction rim of metallic s might form, otherwise not. Is it also not possible that th roded silicates of the norite may have been absorbed by t phide magma and combined with a portion of its mate form some of the inclusions or silicates in the ore? It a to the writer that our knowledge of replacement or corro silicates by a heavily charged sulphide magma is insuffic such a possibility to be lightly dismissed on account of the a any metal-bearing slag in the ore. Such absence would no sarily indicate the action of solutions.

The advocates of a hydrothermal origin point out that the sulphides pyrrhotite is the oldest and is cut and surr by pentlandite and chalcopyrite. The last two have a c habit, but chalcopyrite is believed to be slightly younger t pentlandite. This order of succession of sulphides is ad in support of deposition by solutions. The minerals of a occur in a successive order of formation, but that does n successive deposition by solutions. The sulphide intrusi be considered a magma overloaded with sulphides, and be expected that its solidification would show a regula similar to the minerals of any rock. Also in this co Howe suggests that the order "would seem to be be plained by the nearly simultaneous cooling of the differ phides that had previously separated as distinct miner pounds, non-miscible, though still molten." In this way to crystallize would penetrate the earlier sulphides.

Thus many of the arguments advanced to support the thermal theory substantiate Howe's part of the proposed esis equally well, and other of the arguments are explaine by either theory. Certain features, however, such as currence of typically aqueous minerals as calcite, se quartz, marcasite, galena, and others, and the alteratio

pyroxene, are clearly indicative of hydrothermal origin. These effects are attributed to the final or hydrothermal phase of mineralization as indicated in the proposed hypothesis. While their widespread effect is recognized, abundant products of hydrothermal deposition and alteration are to be found only in the offset deposits, notably the Worthington Mine. The writer believes that only a minor part of the ore bodies has been contributed by the hydrothermal solutions and that their work has been chiefly an unequal permeation of the rock producing alteration; the contribution to certain of the offset deposits of the uncommon and untypical aqueous minerals; probably an enrichment of some of the offset deposits in copper and the precious metals, and the rearrangement of some of the previously formed sulphides, such as has been mentioned by most investigators.

The reasons why hydrothermal processes are limited to the above features and are not concluded to account for all of the deposits have already been considered. It may be seen that hydrothermal mineralization of this nature superimposed upon previously formed ores would confuse characteristics of the previous processes, and a study of those places most affected would give rise to the impression that all of the ores have been formed by hydrothermal agencies. The hydrothermal origin of the Sudbury ores has attained in the literature a position hardly justified, because observations antagonistic to the segregation hypothesis have been applied as convincing arguments in support of it as a single working hypothesis when they are capable of more than one interpretation if applied to multiple working hypotheses.

SUMMARY.

A review of the literature indicates that the origin of the Sudbury ores is a controversial question that is by no means settled as yet. One school of geologists advocates an origin by magmatic segregation whereby sulphides have settled by gravity to the bottom of the intrusive sheet of norite and collected in favorable places to form ore bodies; another school advocates an origin by means of hydrothermal agencies. A modification

of the magmatic theory has been advanced to explain the ores by differentiation in the magmatic reservoir below and intrusion in the form of molten sulphides. A modification of the hydrothermal theory would account for the ores as having been introduced at a late magmatic stage as a result of mineralizing solutions without the formation of secondary silicates. Plausible and convincing arguments for all of these hypotheses are advanced, yet no one theory will explain adequately all of the observed phenomena, nor will it hold against some of the antagonistic arguments of the others. It has appeared to the writer from his discussion of the different views that the Sudbury phenomena cannot be accounted for by any single hypothesis, but can be explained readily by an hypothesis of progressive mineralization which embraces parts of all of the previously advanced hypotheses. He therefore advances the hypothesis that the Sudbury deposits were formed in minor part by magmatic segregation in situ from the nickel eruptive, thereby accounting for the pyrrhotite-norite and some of the marginal ore; in greater part by an intrusion of magma overcharged with sulphides formed by differentiation in the magmatic reservoir beneath, thereby accounting for the greater part of the main marginal bodies and the offset deposits; in minor part by hydrothermal solutions that circulated as an after effect of the intrusions and produced the hydrothermal alteration of the rocks, the later rearrangement of the minerals and the deposition of the typically aqueous minerals such as occur notably in the Worthington mine.

This hypothesis is proposed with more security, since it does not conflict with observed evidence and harmonizes many of those conflicting arguments advanced for single hypotheses which have become controversial points among advocates of other hypotheses

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